UNIT SEPARATION PROCESSES IN SPACE

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ABSTRACT

Some unit separation processes used for purifying chemicals and biologicals (vaccines) are clearly affected by the earth's gravity and therefore might be improved by operation in space. Centrifugation and electrophoresis are the prime examples of such processes. Meanwhile other processes such as freeze drying and ultraviolet sterilization are desirable adjuncts in a spectrum of processes that could permit the complete preparation of vaccine or other materials in space. The freeze drying operation would take advantage of the low temperatures and vacuum of space.

These processes are being considered (by a team of General Electric and Wyeth Laboratories personnel, under contract NAS 8-24683) as a spectrum of interrelated processes that could lead to the complete preparation of vaccine or to the preparation of materials to be used in other processes and products.

INTRODUCTION

In generating, collecting, and assessing ideas for the space processing of materials, it appears that for both economic and technical reasons an integrated sequence of processes may be both desirable and necessary. From the economic viewpoint, it appears that the pre and post flight processing may well outweigh the contributed value of the operations performed in space. Unless the space operation such as zero g melting and solidification, does provide such unique set of properties, as we all hope it does, in the material that the value of this new product is greatly enhanced, the economics will be difficult to justify. From the technical standpoint, there may well be products of great economic and humanitarian value that must be completely processed through all stages in a relatively short time because of chemical or biological instability problems at various steps during the processing.

In the latter category, it appears for example, that vaccine preparation in a free rotor centrifuge or in the electrophoresis process using fluid suspensions may be improved by performing the separation in space under the nearly zero g conditions which provide nearly zero convection. However, the storage of such products on a space station before and after performing either of these operations in space would be undesirable if not impossible. It would therefore appear necessary to also perform the entire spectrum of processes to provide a finished product in space. In the case of vaccine, this might include: (1) the preparation of a virus culture, (2) the separation or purification process such as centrifugation or electrophoresis, (3) freeze-drying and (4) ultraviolet sterilization. Almost the entire space environment of radiation, low temperature, vacuum, ultraviolet, and low gravitational forces would be utilized. Although we can achieve comparable vacuum, low temperatures, and radiation (e.g. ultraviolet) here on the earth, we may well want to use the zero g for the separation processes and will then need to use the other aspects of the space environment for completing the vaccine preparation in an expeditious manner in order to obtain a more stable end product than would be the case if we only did the separation process in space.

In addition to the proposed study of the preparation of vaccine in space, there are potentially other products which can benefit from space processing and which require one or another of these unit processes. These include isotopes, chemicals, and food or food supplements.

Studies of each of the unit processes mentioned has recently been undertaken and a progress report on the work is presented here. It appears even at this early point in the study, however, that both electrophoresis and freeze-drying are attractive candidates for early space processing experiments.

They appear to be easy to design, build, and operate as space experiments and would be timely to perform as necessary steps in the development of an integrated space processing sequence for vaccines. The free rotor centrifuge is still under study but is not as ready for a definite recommendation as are the other two processes. However, there are clear cut cases of detrimental effects of gravity on the operation of conventional centrifuges so that a space experiment should be considered and planned even with a conventional centrifuge which could then be modified to permit the operation of a free rotor centrifuge at a later time.

"In the present course of vaccine development, a major consideration is the possible oncogenicity (tumor production) by viruses. Some viruses which are now used to produce experimental (and important) vaccines have the capacity to produce cancer in certain animals. Extensive studies have been underway in our laboratory to define conditions which would not only make such vaccines safe, but would also make possible the production of a cancer-virus where such becomes feasible using the present tumor viruses as prototype systems. There is already evidence that at least one form of cancer in man is produced by a virus and no suitable vaccine type is available or can be made with present knowledge.

Our approach has been to develop absolute separation methods with the intention of physically or chemically separating the antigenic (immunologically potent) proteins of the viruses from their genetic material. With such an approach one could be assured that such a possible cancer vaccine would not itself have the potential of producing tumors in the vaccinated subjects.

Attempts have been made to separate the protein structures by various forms of chromatography and electrophoresis. Similar separations have also been attempted by means of high speed gradient ultracentrafugation. In none of the earth laboratories has it been possible to obtain absolute separations by such physical means.

The space laboratories offer the possibility of greatly improving the precision with which physical separations can be done since the electrical or centrifugal forces employed can be isolated from the gravity forces that tend to diffuse the components. Although these diffusions may be only a very small percentage of the total movement of the components, the current problems require much more absolute separations. It could, therefore, be of great value to achieve such separations in zero gravity laboratories."*

CENTRIFUGES

The ultracentrifuge has historically been an important analytical tool for researchers in the chemical and biological fields. Until recently it was not widely used commercially, however, due principally to its small throughput. Recent developments at Oak Ridge National Laboratories and commercialization of these designs by several organizations indicates a large and increasing interest in the centrifuge for preparing high quality biologicals and pharmaceuticals. These have obviously great and well accepted economic and humanitarian value.

In parallel with this development, several organizations have been considering the possibilities for improving materials and processes in space. One of the ideas that we have been studying is that a simple rotating machine, such as a centrifuge rotor would not need bearings to operate in space. Further, it would not then have the mechanical connections through which vibrations and heat could be conducted and it should therefore perhaps yield better separations

*private communication by Dr. B. A. Rubin

by this minimizing of vibrations and convection. A review of literature on the use of centrifuges indeed indicates that these are two of the three most prominent problems with centrifuges. The third problem is often thought to be the only or the principal problem. It is related to the strength of materials and therefore the size or maximum peripheral speed of a centrifuge. Operating a centrifuge in space will not markedly improve this situation, although the new advanced composite materials may well do so. A second order problem in certain research uses of centrifugation is incidentally due to the presence of gravity which causes sedimentation during long (several days) runs. In spite of the large g forces acting normal to the (vertical) axis of a centrifuge the one-g force of the earth causes undesirable sedimentation.

These several aspects of centrifugation appear therefore to be prime reasons for further considering the development and operation of centrifuges in early space experiments.

The initial consideration in our study of centrifuges is on the vibration problem and this is presented here. Convection is also of direct interest in the operation of a centrifuge as well as in electrophoresis. However, for convenience it is discussed in the next section under 'Electrophoresis'.

Basically a centrifuge is an elastic cylindrical body with a liquid cavity. It is well known from the dynamics of elastic containers with liquid cavities that a partially filled cavity behaves very differently from the fully filled cavity and the empty cavity. It is observed in the operation of centrifuges that a "partially filled centrifuge can undergo dangerous oscillations, the amplitudes of which exceed considerably the amplitudes of oscillation of the empty or fully filled centrifuge." (Ref. 1) As a first cut model we chose a fully filled centrifuge so that a simple model for analysis could be studied to yield preliminary comparisons. The equations of an elastic container with a fully filled fluid cavity are completely analogous in form to those of solid elastic body with internal friction, the contribution of the fluid appearing in the internal friction terms. Thus the first cut model reduces to a cylindrical rotor with internal friction and if the cylinder is long compared to its diameter the basic first cut problem is a rotating shaft with internal friction.

The boundary conditions and energy requirements necessary to maintain a constant angular velocity differ in the operation of the centrifuge in a normal or in a weightless environment. On the Earth it is necessary to support the centrifuge and the boundary conditions are at best self-aligning bearings. In a weightless operation the centrifuge can be freely floating and bearing-free operation is possible. On the Earth energy must be supplied to maintain a constant angular velocity whereas in space no drive is required to maintain the free rotor after it attains the desired rotation rate. These are very important differences. The presence of support bearings means the presence of external friction and oscillations due to motions at the bearings. The necessity for supplying energy to maintain the rotation rate is an even more severe problem. The basic principle of building up vibrations in a flexible shaft is: "If the drive maintains a constant angular velocity irrespectively of the behavior of the shaft, then under certain conditions part of the energy supplied by the drive is absorbed in lateral oscillations; internal friction and similar factors then act simply as transmitters of energy." (Ref. 1) For a free rotor where it is not necessary to supply energy to maintain the rotation, there is no energy source to sustain lateral vibrations. Thus from energy arguments, a bearing-free rotor not operating at its critical velocity should not develop undesirable lateral vibrations if not disturbed.

Let us consider the centrifuge as a cylindrical elastic solid rotating about its cylindrical axis at angular velocity, "ω". If the cylinder is long compared to its diameter we can consider it as an unloaded rotating shaft. The following is observed when the rotation speed of an unloaded shaft is increased: It is found that a certain speed, called the critical speed, is reached at which instability will occur, the shaft deflecting into a single bow and whirling around like a skipping rope. If this speed is maintained the deflection will become so large that the shaft will be fractured; but if this speed is quickly run through, the shaft will become straight again and run true until at another higher speed the same phenomenon will occur, the deflection now, however, being in a double bow, and so on to the next critical speed. These are the critical resonances which are encountered in running up or slowing down a centrifuge to a desired rotation rate and these oscillations at the critical speeds will cause remixing of components and, if the centrifuge has not been designed properly, fracture of the rotor. It is further found when

considering the presence of internal and external friction that these critical speeds become critical regions through which lateral vibrations are sustained. Further, there may be a tendency to self-induced transverse vibrations at speeds other than the critical. In running up a centrifuge to a rotation above a critical speed, energy much be supplied; and thus, whether fixed or free, the critical resonance and the tendency to self-induced oscillations will be encountered during this phase and also during slowing down. It is in the operation at constant rotation rate that the free and supported centrifuges differ as has been stated above.

In practice, of course, no shaft or centrifuge rotor can be made perfectly straight or uniform in mass distribution. Thus practically we should begin with an initial bent configuration and a mass eccentricity distribution. Initially the problem we chose had no internal or external friction terms. The reason for this is that at this time we want to make a rough comparison of the critical speeds of a bearing-free centrifuge and a centrifuge constrained at each end by self-aligning bearings. Further analysis should be performed that will include both external and internal friction, mass eccentricity distribution, etc.

Sketches of the fundamental shapes associated with various resonant frequencies for both a free rotating shaft and a rotating shaft with self-aligning bearings are shown in Figures 1 and 2 respectively. Mathematical solutions for both cases were obtained (by G. Wouch) and are reported in the first quarterly progress report under this contract. The conclusions are summarized in Table I as the ratio of critical frequencies of free and restrained rotors.

TABLE I

Ratio of Critical Frequencies of Free and Bearing-Restrained Rotors

Mode	2	3	4	5	6
$\frac{\text{Free}}{\text{Self Aligning}}$	2.2	1.5	1.3	1.2	1.2

The ratio of critical frequencies is 2 for ω_2 and the free shaft's critical frequency is twice that of the shaft with self-aligning bearings.

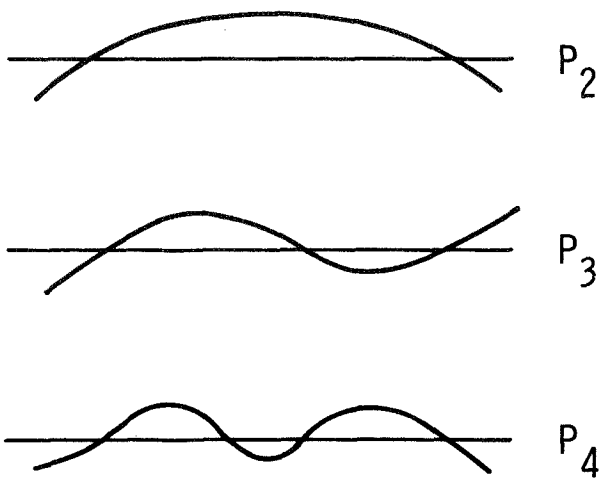

Figure 1. Fundamental Shapes Assumed by a Free Rotating Shaft

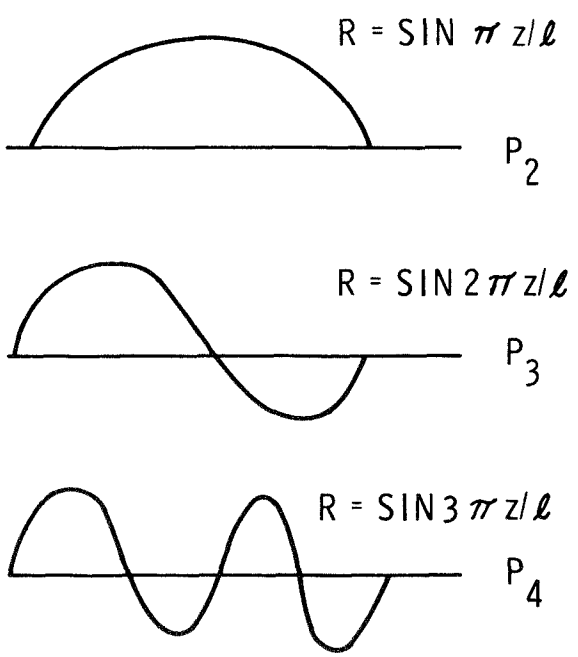

Figure 2. Fundamental Shapes Assumed by a Rotating Shaft with Self Aligning Bearings

We have considered here basically a bearing-free centrifuge and a centrifuge constrained at each end by self-aligning bearings, neglecting the external friction and internal friction terms. There are two basic conclusions that can be drawn from this simple comparison:

1. The first critical frequency of the free centrifuge is about twice that of the constrained centrifuge so that it could be operated at about twice the rotation rate of the constrained centrifuge before the first resonance is encountered;

2. The shapes assumed by the free centrifuge are different from the constrained centrifuge and there is a smaller deviation from the unbent configuration for the free centrifuge than for the so constrained centrifuge.

Dimentberg (Ref. 2) has succinctly and concisely summarized the steady state behavior of a rotating shaft: "The following picture can be built up for steady state movement of an unbalanced shaft at a constant speed of rotation. Under the action of unbalance forces and inertial forces, the shaft is subjected to static bending; its spatial elastic line is the superimposition of the harmonics of successive orders $(1, 2, 3, \ldots)$ each of which lies in a certain plane, the planes of the harmonics generally being different, since the coefficients are complex. The combination of the planes with the harmonics lying in them forms a 'rigid' configuration, rotating with the shaft with an angular velocity ω. The relationship between the moduli of the harmonics and also between their phases are disturbed when there is a change in the angular velocity ω." The effects of external and internal friction have not been considered.

Explicit in the development of the basic equations of the rotating shaft, neglecting friction terms, are the presence of external torques and forces. Driven centrifuges on the earth will indeed have unbalance forces and torques exerted on them even at constant angular velocity and so are treated either as rotating shafts with a disk attached or as rotating shafts. A bearing-free centrifuge rotating at constant angular velocity does not have this source of energy, and the dynamics of a free centrifuge rotating at constant angular velocity are very different from those of centrifuges on the Earth.

ELECTROPHORESIS

Electrophoresis refers to the movement of colloidal particles and macromolecular ions under the influence of an electric field. It is often the only method available for the quantitative analysis and fractionation of biological materials. While early work with the process was based on fluid suspensions, the difficulties imposed by convection and sedimentation have caused most of the recent work to be performed on a solid support such as paper or in gel-filled apparatus. There are cases, however, where successful purifications have been accomplished only in fluid sols. But while minute amounts of material can be fractionated for analysis by zone electrophoresis in the fluid state, the use of this technique on a preparative scale is severely limited by convection and sedimentation. It therefore appears to be desirable to operate a fluid state electrophoresis apparatus in space where convection and sedimentation would not be problems. It appears that a relatively simple apparatus could be designed for such an experiment. The primary requirements are that the apparatus remain filled with liquid regardless of addition or removal of material and that the apparatus be capable of being filled or emptied without being opened. We believe that both these requirements can be met.

The basic concept behind electrophoretic separations is the difference in rate and direction of migration of the components of the sol in the presence of an electric field. A sol containing many components will tend to separate into bands of a single species and if all the components have the same sign of charge the bands or zones will drift with velocities characterized by their respective electrophoretic mobilities toward either the cathode or the anode and could ideally be collected as they approached the electrode one at a time. This would be the ideal case of zone electrophoresis. Unfortunately there are many practical factors which make this ideal separation process more difficult, especially for scaled-up production.

While it is by no means the only consideration, the elimination of convection has been a major driving force in the development of paper electrophoresis, electrochromatography in slabs of porous material, continuous flow electrophoresis, and column electrophoresis in granular media, gels, and density gradient solutions. These methods have met varying degrees of success, but all

introduce some new problem such as loss of electrophoretic mobility, electroosmosis, precipitation of colloids, contamination of product with gel or density gradient material, minute sample size, and poor resolution.

The simplest effective electrophoretic apparatus is that of Tiselius (Figure 3). "The U-tube portion is in three parts, 1, 2, 3, which can slide horizontally with respect to one another. The lower parts 1 and 2 are filled with a buffer solution of known pH in which the proteins are dispersed. The part 3 which has been pushed aside, is then filled with the buffer solution alone and slid over to complete the U tube and establish a sharp boundary in each limb. Each of the large vessels 4 contains a silver chloride electrode 5. In the immediate vicinity of the electrode material is a concentrated solution of alkali-chloride, but the remainder of each of the vessels is filled with the same buffer solution as in the U tube, so this is continuous through the apparatus. A source of E.M.F. is then applied to the electrodes and electrophoresis commences; separate boundaries are formed due to the different speeds of the different protein molecules at the pH of the medium. By keeping the temperature at about $3^{\circ}C$, the point of maximum density of the buffer solution, convection effects at the boundaries due to heating by the current are minimized." Schlieren optical techniques are used to observe the positions of the boundaries. The sharp change at a boundary becomes apparent as a peak in the Schlieren pattern, and each boundary produces such a peak. A typical pattern is shown in Figure 4. For substances of low molecular weight, high voltages are generally employed because during a long running time the zones will tend to spread due to diffusion and good separations may not be obtained. For substances of high molecular weight, longer running periods can be employed because diffusion is relatively slow. This is advantageous in biochemical work because relatively low voltages and long running times may be employed to effect a separation.

Zero-gravity electrophoresis might be carried out in a straight glass tube with electrodes at either end and a means of collecting the fractions. It may be necessary to immerse the electrodes in potassium chloride solution and to isolate them from the sample with glass frits. Low voltages and long running times are contemplated. Initially non-hazardous biological materials should probably be separated. The initial experiment might involve a

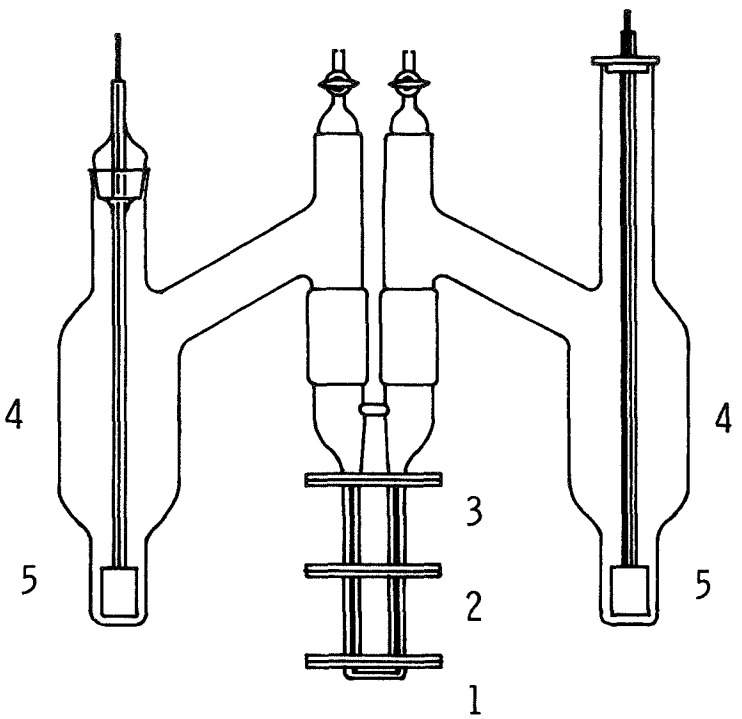

Figure 3. Tiselius Apparatus

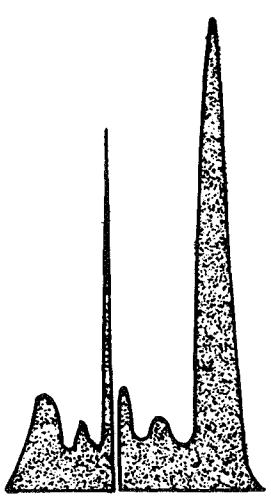

Figure 4. Typical Schlieren Pattern for Separation of Proteins

simple scaled-up replication of some typical blood serum separations to show proper operation of the apparatus. Then a more valuable fractionation will follow, possibly separation of a vaccine in significant quantity.

CONVECTIVE TRANSPORT

Before beginning a discussion of convective transport it is well to keep in mind that convective transport is to be avoided in electrophoretic as well as centrifuge separations as it leads to remixing of the colloidal particles we are trying to separate. Convective transport of a fluid is the motion of a body of fluid immersed in a fluid due to buoyant forces acting on the fluid body.

There are two distinct kinds of convection: (1) slow convection which takes place when the gravitational potential energy is converted directly into heat and the inertial forces are negligible; and (2) penetrative convection which takes place when almost all the gravitational energy released is converted into visible bulk motion and remains such for a long time.

SLOW CONVECTION

Slow convection can be set up in the following way:

- Consider two metal plates placed horizontally one above the other with a fluid in between and let the upper plate be free to rise a little

- Gradually raise the temperature of the lower plate. The fluid in contact with it is warmed, it expands and its density decreases.

- The thermal (molecular) conductivity of the fluid will transfer heat upward through the layer of fluid even when there is no bulk motion. If the lower plate is warmed slowly enough it can be ensured that the temperature gradient in the layer is practically uniform.

The criterion for warming up the bottom plate without setting the fluid in motion is that the thermal conductivity must transfer heat upward to the cold plate more quickly than if there were some motion.

If motion does take place it must be upward in some places and downward in others. See Figure 5. Warm fluid at A will be placed side by side with cool fluid at B_1 and B_2 and the thermal conductivity will begin to conduct heat horizontally, which will take heat from the fluid going upward and give it to the fluid going downward. This is a tendency to oppose the conduction of heat upward. These adjacent layers can not be far apart because the fluid would have to travel a large horizontal distance on reaching the other plate in order to return (a great deal of gravitational potential energy would have to be expended against viscosity in this horizontal motion and also a particle travelling to A would acquire enough heat to rise long before it reached A). They can not be too close because in addition to the wasteful horizontal conduction there would also be viscous forces resisting the relative motion of the closely placed up and down currents.

There is one optimum configuration (Figure 6) which can occur if the temperature gradient exceeds a certain minimum value related to viscosity and thermal conductivity. The shape of the cells is independent of the actual values of the physical quantities and is the same in all fluids (hexagonal or square). Experimentally it has been established that the direction of motion in the center of the cell is toward the region of smaller viscosity and for gases μ is proportional to T (downward at the cell center), for liquids μ is proportional to T^{-1} (upward at the cell center).

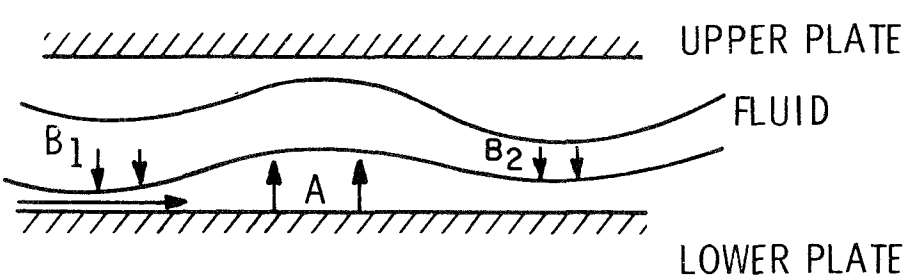

Figure 5
Incipient Slow Convection

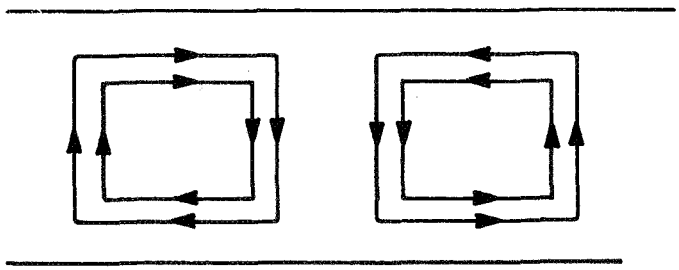

Figure 6
Representation of Slow Convection

The conditions under which slow convection is initiated are calculable from properties of the fluid. The density gradient required to start motion is:

$$\frac{g(\rho_b - \rho_t)}{L\,\rho_b} = K\left[\frac{\kappa}{\rho_b C_p}\right]\left[\frac{\mu}{\rho_b}\right]\left[\frac{1}{L^4}\right] ,$$

where:

g	=	gravitational acceleration	η	=	thermal conductivity of fluid
ρ	=	density			
L	=	height of layer	μ	=	viscosity of fluid
K	=	reciprocal of the Rayleigh number	C_p	=	specific heat capacity

subscripts "b" and "t" refer to "bottom" and "top"

Rayleigh found that

$$K = \frac{27}{4}\frac{\pi^4}{} \approx 670$$

though other values as high as > 1700 have also been reported.

Expressing density differences in terms of thermal expansion coefficient and temperature differences, and rearranging terms gives the equation in the form

$$\frac{g \rho^2 \beta C_p L^3 \quad Tb - Tt}{\varkappa \mu} = K$$

It is found that, K, the reciprocal of the Rayleigh number depends upon:

(a) the motion is slow: the inertia forces are negligible (Reynolds Number small)

(b) the temperature and density differences are small, being only small fractions of their absolute values

(c) β, $\varkappa$, C_p, μ are independent of temperature over the range

(d) the conditions at the boundary are the same for temperature and velocity,

(d) all the heat that goes in at the bottom comes out at the top.

PENETRATIVE CONVECTION

Putting in heat too rapidly means that requirement (a) above is violated, the motion is not slow and the inertia forces are not negligible so gravitational potential energy is converted into bulk motion as well as heat. The warm fluid rises in lumps, hits the other surface and spreads out forcing fluid down. The cells appear to grow from nothing to a very large size, and as they get bigger cells form within them giving rise to a quite chaotic and undesirable mixing motion as shown in Figure 7. A free upper surface becomes noticeably unlevel and may bulge upward if the bulk motion is large enough.

If (a) and (c) are violated then motion described above occurs. The lumps are called thermals. The thermals mix with the surroundings as they advanced and grow bigger. Between the core and the surrounding fluid where the density gradients are greatest the fluid is made to rotate. It is carried around into the rear of the thermal.

When it reaches the central region the vorticity begins to be slightly reduced because the fluid surrounding it is now more buoyant. The core is forced to advanced within the thermal because it is the most buoyant part of it. The points of zero motion relative to the thermal advance outward along the line bounding the region of mixing.

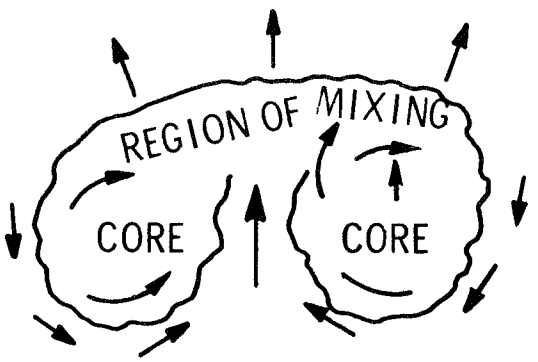

Figure 7. Penetrative Convection

FREEZE-DRYING

" Lyophilization or freeze-drying is the removal of water from biological materials while in the frozen state. This process has long been used for the preservation of certain biological and biochemical properties. More recently, it has gained wider application in the preservation of organs and blood supplies.

Lyophilization may be a necessary adjunct to other processes carried out with biochemicals in space. For instance, if a separation process such as centrifugation or electrophoresis is used to purify a vaccine, lyophilization will be desirable or perhaps necessary to maintain the potency and safety of the product until the next shuttle can return it to earth.

Of further interest is the use of special lyophilization conditions for the production of unique biological products. In this category we may consider the preparation of vaccines for rabies or the arbor viruses. In both of these cases, the ability to produce suitable

vaccines has been limited by the difficulty of inactivating the viruses in a manner that suitably preserves the antigenicity (immunizing capacity) of such vaccines. We have preliminary evidence from our own experiments that high vacuum conditions may hold an answer to these problems.

A great deal of related work on the lyophilization and preservation of biological materials is available in the literature. We have conducted extensive experiments on the characteristics of lyophilized virus and virus antigens. Although some such preparations have indeed been very successful, a number of problems still remain which are difficult to resolve with existing equipment. When lyophilizing extremely minute volumes of viruses, we have been able to demonstrate that the bound water of the virus particle can be removed in a manner which inactivates the virus. Presumably, since the protein antigens may not depend on their water content, one can expect that the antigenicity will be preserved while it may be possible to destroy the dangerous viability. The investigation of this phenomenon is a space laboratory may be warranted as an adjunct to other processes.

Additional work has been done on the problem of the passage of water vapor through semi-permeable membranes of various polymer or rubber compositions. It appears feasible to permit lyophiliz ation through such membranes in space. Such an enclosed lyophilization procedure would have a number of advantages. It would, for instance, permit the lyophilization of important but very dangerous agents in a manner which would not create hazards. This technique may be essential for space lyophilization since the product could not easily be contained without gravity. Even in ordinary lyophil apparatus the fluffy, dried powders tend to escape." *

A space experiment on the freeze drying of virus is recommended. As currently visualized it would consist of a small (perhaps 6" x 6" x 6") chamber connected by a several inch diameter (valved) pipe to the exterior vacuum in the wake of the spacecraft where reportedly a very low pressure (10^{-10} to 10^{-12} torr) may be available. A heat pipe or similar heat transfer device would permit the initial freezing of the product and would be used in conjunction with heaters to control the product at the desired temperature.

*Private communication by Dr. B. A. Rubin

The initial experiment could be performed with or without the use of a condenser to collect the effluent water; however, it is envisioned that any eventual scale-up of this type of process would involve recovery and reuse of the water for economy reasons.

Artist's sketches of equipment for space experiments with Free Rotor Centrifuges, Zero-G Electrophoresis, and Freeze-Drying are shown in Figures 8, 9 and 10 respectively. In Figure 8 a free rotor centrifuge (lower right) is shown with a torquer (lower left) which would be used on two rotors to spin them in opposite directions. The centrifuge has a chamber containing tanks to hold the various solutions and suspensions used in the preparation and purification of biologicals. Figure 9 shows a fluid filled electrophoresis cell for use in space experiments. Figure 10 is a freeze drying chamber for vaccines or other chemicals. A heat pipe, the small tube in the lower left, is a potential means of providing cooling to the sample holder plate. The valved vacuum pipe is shown as extending through the rear bulkhead of a space vehicle to permit use of the reportedly very low pressures achievable in the wake of the vehicle.

ACKNOWLEDGEMENT

The ideas and work behind this presentation are by no means entirely that of the authors, although they accept the responsibility for the presentation. Many of the ideas and analysis came from others and in particular, Dr. R. T. Frost and Gerry Wouch, of General Electric Space Sciences Laboratory and Dr. B. A. Rubin of Wyeth Laboratories, deserve great credit for their contributions to this work.

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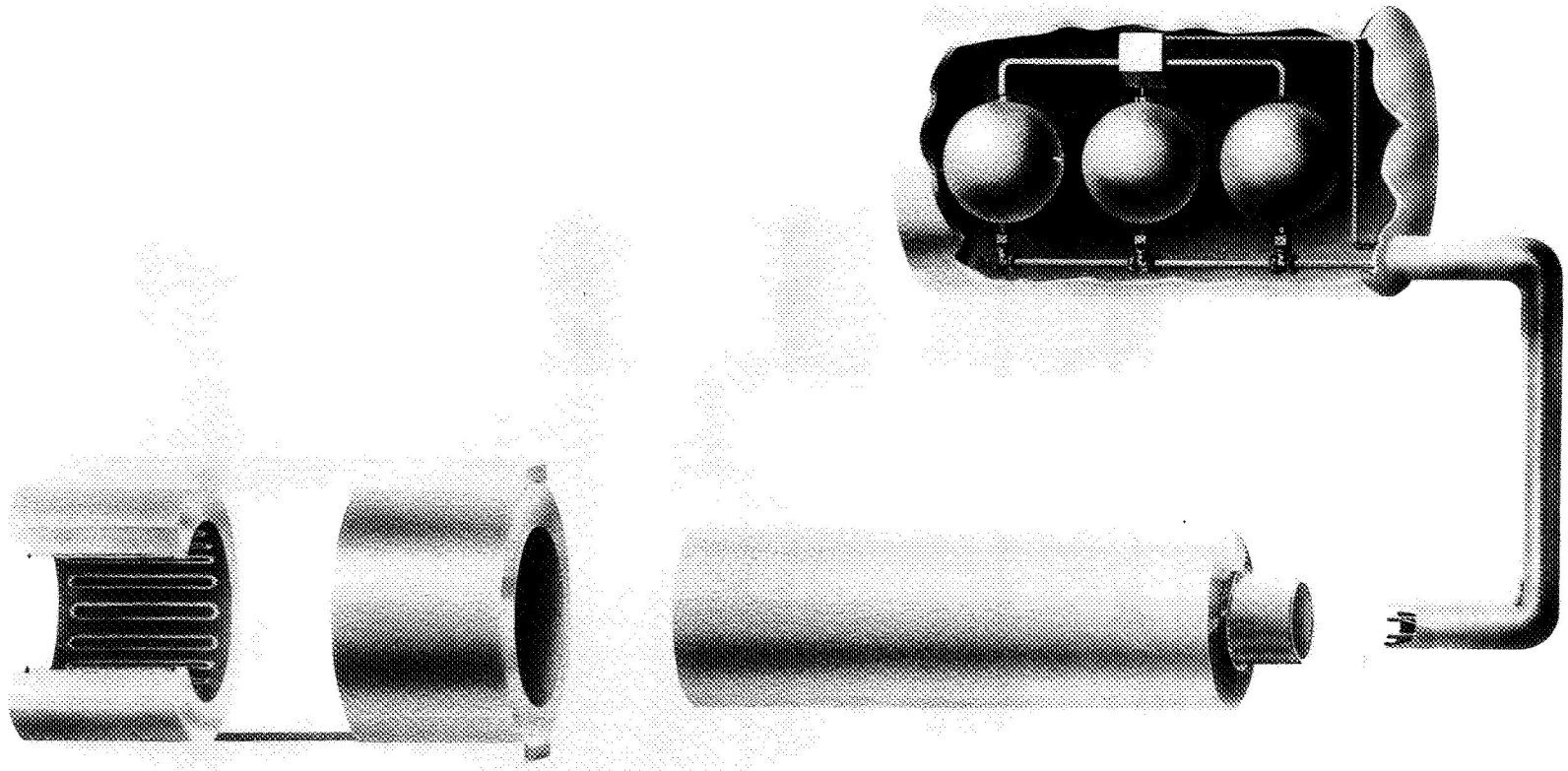
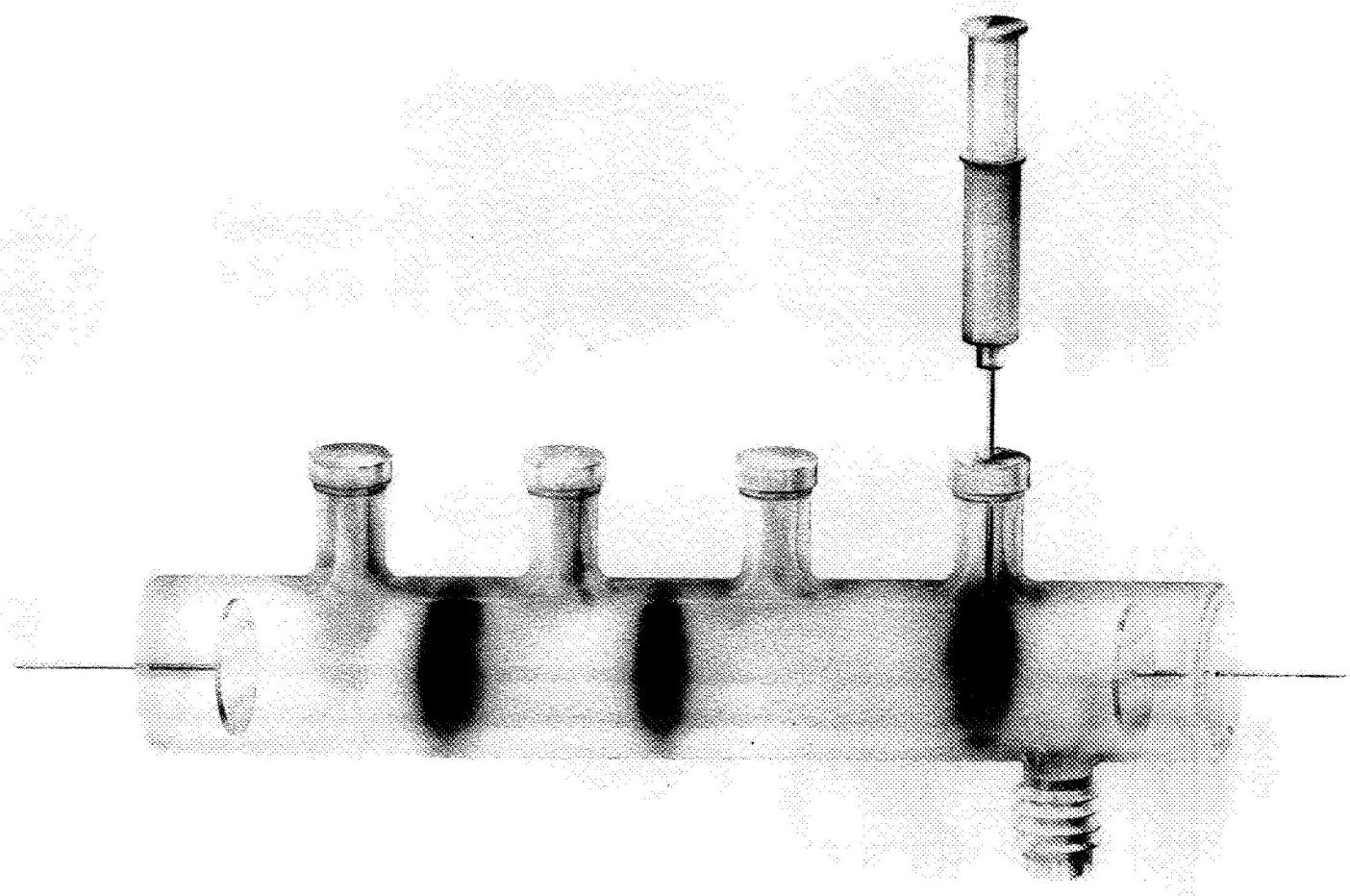


FREE ROTOR CENTRIFUGE

Figure 8



ZERO-G ELECTROPHORESIS

Figure 9

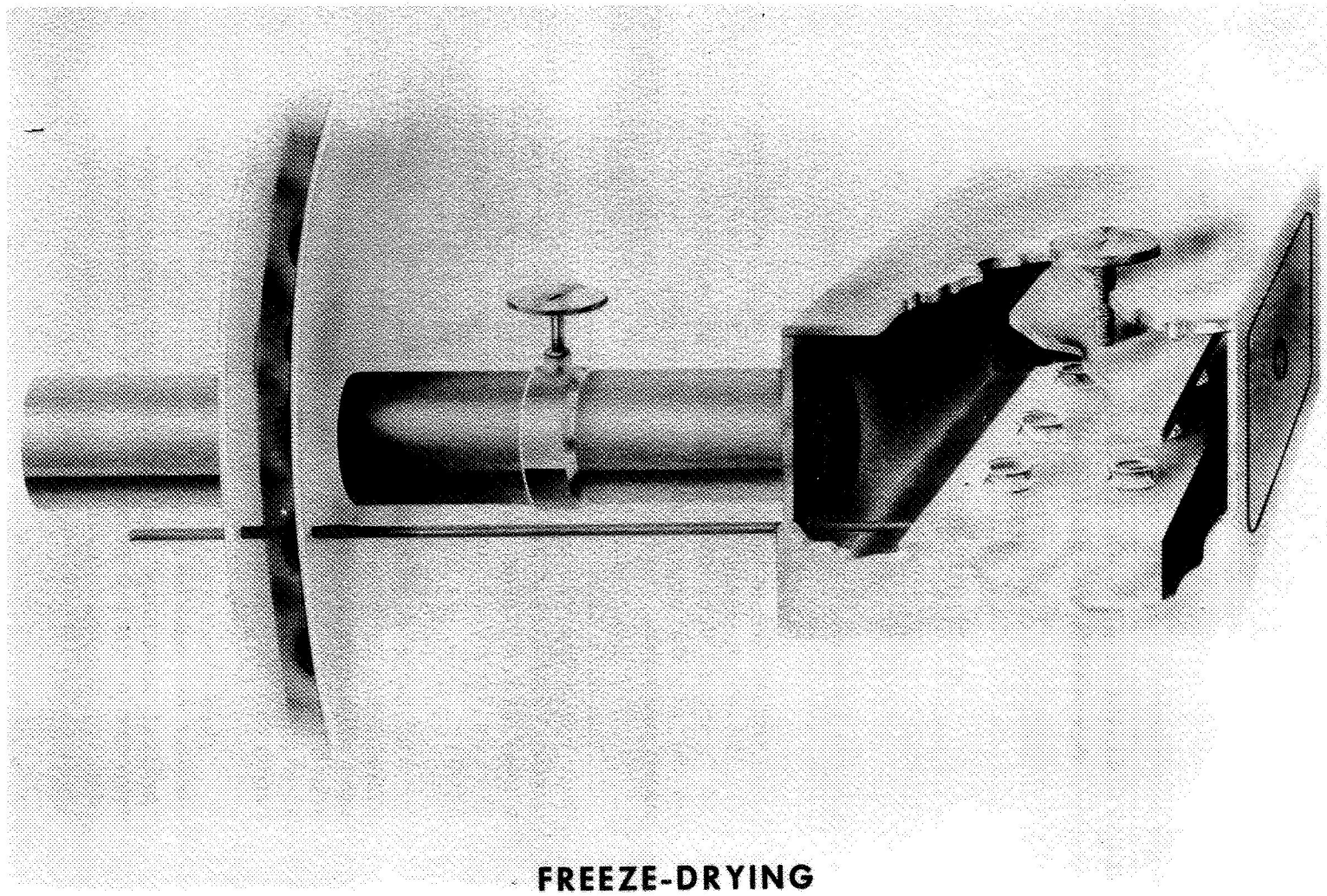


Figure 10